Antenna Based Signal Processor Using Reconfigurable Receiver

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Abstract — **A reconfigurable receiver structure is demonstrated in this paper, where the receiver could be tuned for the optimum reception or rejection of the radio wave with any form of polarization. Such a receiver is enabled by digital or analog processing on the outputs of a dual polarized antenna. A closed form expression of the down-conversion matrix is presented for the received signal processing. Demonstration of this receiver for various polarized waves is also presented using RFIC components. The experimental results demonstrate cross polarization rejection of at least 14dB for linearly polarized and 18dB for circularly polarized waves over 500 MHz at 2.45GHz.**

Index Terms — **reconfigurable receivers, polarization diversity, dual polarized antenna, diversity reception, signal processing antenna.**

I. Introduction

Base stations and mobile terminals overcome the fading effect in a mobile radio channel [1, 2] through polarization diversity feature, which also allows the frequency reuse by employing cross-polarized radio waves [3, 4]. This technique is also being researched for beam steering and multiple-input multiple-output (MIMO) antenna array systems as a means to increase the channel capacity [5]–[9]. In particular, dual polarized patch antennas are used on mobile terminals and antenna arrays because of its low cost and integration capability [10]. Realization of circular and linear polarization antennas are reported with various feeding methods [10]–[12] and with low cross-polarization or high isolation [13]–[15]. Such properties help reduce the cross-talk at the receiver and increase channel capacity. In addition, *analog signal processing* functions could be employed in a MIMO system as a multi-path mitigation method in conjunction with the commonly employed digital signal processing techniques.

This analog signal processing function could be also employed in polarization-agile applications, where the polarizations of a receiver need to be changed after installation [16] by switching antenna polarization. The number of polarization modes of this type of antenna is limited by the matching circuits and feed locations. Typically two orthogonal polarization modes can be selected [17]. Common polarization combinations include: vertical, horizontal, +45°, and -45° of linear polarizations (LP), and left hand and right hand circular polarizations (CP).

In this paper a reconfigurable receiver with tunable polarization is proposed for the above mentioned applications. Any arbitrary polarization of the receiver is created by analog or digital processing of the output signals of a dual polarized antenna. Dual or multiple RF receptions of any arbitrary polarized waves is achieved. The system architecture of this reconfigurable receiver is described in the section II. Next, the full analytical modeling of this robust receiver is presented in section III. Finally in section IV the experimental results of a prototype system are presented at 2.45GHz.

II. Receiver Structure

The topology of the reconfigurable receiver is shown in Fig. 1, where the gain and filtering blocks are excluded for simplicity. This receiver has three parts: a dual polarized antenna, a RF front-end receiver circuit, and a phase tuning circuit. The arbitrary polarized antenna outputs (either LP or CP) are from a ring antenna, as depicted in Fig. 1a. Any dual polarized antenna with dual linearly polarized or dual circularly polarized output works with the receiver. Broadband annular ring-reported with excellent axial ratio characteristics [18 - 19] are good candidates for this topology. The front-end down-converter consists of bandpass filters (BPF), low-noise amplifiers (LNA), two mixers, and two baseband amplifiers (BA), as shown in Fig. 1b. The local oscillator (LO) signal that is generated by a signal source is separately shifted by two phase shifters, and the output signals (i.e., LO1 and LO2) are used to drive the RF down-converter mixers. These large-signals are phase shifted version of the same coherent local oscillator (LO) signal, as shown in Fig. 1c. Many forms of digital phase shifters can be used here. The required phase difference between LO1 and LO2 depends on the type of antenna and the polarizations of incoming wave. There is no need for passive polyphase circuit in the front-end circuitry with the receiver.

III. Theory of Operation

We analyze the situation that practical waves and antennas are used in the receiver. Two signals that are generated by a pair of practical cross-polarized antennas are shown in Fig. 2. Such waveforms could be emitted by a dual linearly polarized antenna oriented for vertical and horizontal polarizations.

The cross-polarized wave pair can be represented by its polarization vectors $\vec{\rho}_1$ and $\vec{\rho}_2$, or equivalently **E1** and **E2.**

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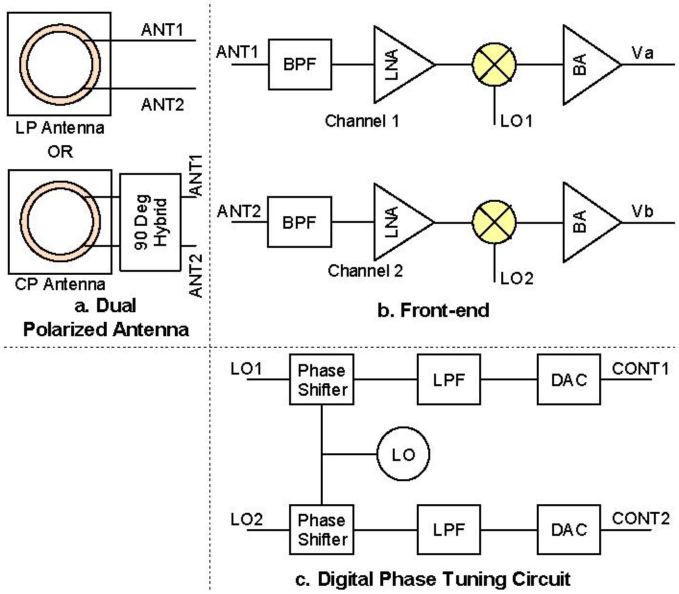

Fig. 1. Block diagram of a reconfigurable receiver for any arbitrary polarization.

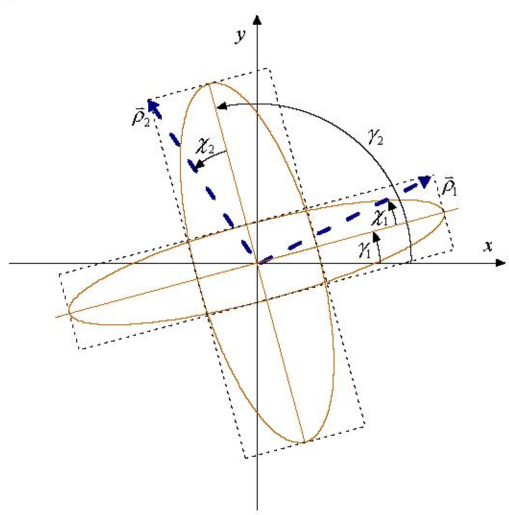

Fig. 2. Two elliptically polarized waves.

$$\vec{\rho}_1 = \begin{bmatrix} \hat{a}_x & \hat{a}_y \end{bmatrix} \cdot \mathbf{E1}, \tag{1}$$

$$\vec{\rho}_2 = \begin{bmatrix} \hat{a}_x & \hat{a}_y \end{bmatrix} \cdot \mathbf{E2}, \tag{2}$$

$$\mathbf{E1} = \mathbf{R}(\gamma_1)\mathbf{P}(\chi_1)\begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{3}$$

$$\mathbf{E2} = \mathbf{R}(\gamma_2)\mathbf{P}(\chi_2)\begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{4}$$

where $\mathbf{R}(\gamma)$ and $\mathbf{P}(\chi)$ are the transfer matrixes of rotation and ellipticity, respectively.

$$\mathbf{R}(\gamma) = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) \\ \sin(\gamma) & \cos(\gamma) \end{bmatrix}, \tag{5}$$

$$\mathbf{P}(\chi) = \begin{bmatrix} \cos(\chi) & j\sin(\chi) \\ j\sin(\chi) & \cos(\chi) \end{bmatrix}. \tag{6}$$

An arbitrary polarized wave is represented by the polarization vector $\vec{\rho}_3$. This wave may also be represented by a new basis function, which consists of the vector $\vec{\rho}_1$ and $\vec{\rho}_2$

$$\vec{\rho}_3 = \begin{bmatrix} \hat{a}_x & \hat{a}_y \end{bmatrix} \cdot \mathbf{E3} = \begin{bmatrix} \vec{\rho}_1 & \vec{\rho}_2 \end{bmatrix} \cdot \mathbf{E3}', \tag{7}$$

The element of **E3'** is calculated as

$$\begin{aligned} E3'_{n=1,2} &= \frac{1}{2}\cos(\gamma_n - \gamma_3)\cos(\chi_n - \chi_3) \\ &+ \frac{1}{2} j\sin(\gamma_n - \gamma_3)\sin(\chi_n + \chi_3) \end{aligned} . \tag{8}$$

With the given coefficient, an arbitrary polarized wave is generated by processing the outputs of a dual polarized antenna. If a quadrature down-converter is employed at each antenna port, such processing can be digitally applied on its inphase and quadrature output signals. However, such operation requires an extensive amount of processing resource for broadband receivers. A tradeoff can be made between bandwidth of the system and the cost of the digital processing units. With the receiver structure in Fig. 1, the backend digital processing load of the receiver may be greatly reduced by applying front-end signal processing in analog domain. A particular case of interest is when only a limited number of polarization methods are required to receiver.

IV. Analog Processing using Reconfigurable Receiver

Significant advantage in the required digital signal processing power outweighs a low level mobile system complexity when added receiver flexibility is attained. The receiver shown in Fig. 1 is configured into different modes, depending both on the transmit signal format and the receive antenna type. Let us look at the following example, where a receiver is driven by a dual linearly polarized antenna with +45° and -45° degree polarization. The signals down-converted by the front end circuit and the two output signals are taken from two baseband amplifiers. With analog circuitry, their sum and difference can be easily extracted.

The signal seen by PORT1 and PORT2 of the antenna is the projection of incoming wave onto the unit vectors at +45° and -45°. If the field amplitudes and phase of the received wave (i.e., E_{ox}, E_{oy}, ϕ_{ox}, and ϕ_{oy}) and the receiving antenna gain of G_r at wavelength of λ are known, the received voltages from antenna are expressed as:

$$\frac{V_{ox}{}^{2}}{Z_0} = \frac{\lambda^2}{4\pi} G_r \frac{|E_{ox}|^2}{Z_{0,air}}, \tag{9}$$

$$\frac{V_{oy}{}^{2}}{Z_0} = \frac{\lambda^2}{4\pi} G_r \frac{|E_{oy}|^2}{Z_{0,air}}. \tag{10}$$

The output signals of PORT1 and PORT2 (i.e., V_1 and V_2) can be calculated as:

$$V_1 = \mathrm{Re}\left[\frac{V_I + jV_Q}{\sqrt{2}}\left(V_{ox}e^{j\phi_{ox}} + V_{oy}e^{j\phi_{oy}}\right)\right], \tag{11}$$

$$V_2 = \mathrm{Re}\left[\frac{V_I + jV_Q}{\sqrt{2}}\left(V_{ox}e^{j\phi_{ox}} - V_{oy}e^{j\phi_{oy}}\right)\right], \tag{12}$$

where V_I and V_Q represents the amplitude of in-phase (*I*) and quadrature (*Q*) portion of the modulated voltage wave. Since the *I* and *Q* received signals are slow varying function of time compared to the carrier signal, they are not expressed in the time dependence form.

The LO1 and LO2 are represented as two carriers with phases of ϕ_1 and ϕ_2 respectively, as depicted in Fig. 1c. The output signals of the two down converters are expressed as:

$$\begin{aligned}\mathrm{V}_a = &\frac{\sqrt{2}}{2}G_1\left[V_I V_{ox}\cos(\phi_{ox}+\phi_1) - V_Q V_{ox}\sin(\phi_{ox}+\phi_1)\right] \\ &+\frac{\sqrt{2}}{2}G_1\left[V_I V_{oy}\cos(\phi_{oy}+\phi_1) - V_Q V_{oy}\cos(\phi_{oy}+\phi_1)\right]\end{aligned}, \tag{13}$$

$$\begin{aligned}\mathrm{V}_b = &\frac{\sqrt{2}}{2}G_2\left[V_I V_{ox}\cos(\phi_{ox}+\phi_2) - V_Q V_{ox}\sin(\phi_{ox}+\phi_2)\right] \\ &-\frac{\sqrt{2}}{2}G_2\left[V_I V_{oy}\cos(\phi_{oy}+\phi_2) + V_Q V_{oy}\cos(\phi_{oy}+\phi_2)\right]\end{aligned}, \tag{14}$$

where G_1 and G_2 are the down-conversion gain of two receiving channels.

Two signals of equal level may be seen at the output of both receiver channels, if the signal waves are equally received by both antenna ports and two down-conversion gains are identical. The reception of the receiver to six commonly used wave polarizations is presented in Table I in terms of common and difference received signal levels, which are defined as:

$$\mathrm{V}_c = \frac{\mathrm{V}_a + \mathrm{V}_b}{2}, \tag{15}$$

and

$$\mathrm{V}_d = \frac{\mathrm{V}_a - \mathrm{V}_b}{2}. \tag{16}$$

The +45° and -45° LP signal are the output of two baseband ports regardless of the LO phase. For the reception of vertically and horizontally polarized signals, LO1 and LO2 should be either in-phase or 180° out-of-phase. The difference and sum of the two down-converter outputs then becomes the desired polarization mode. An interesting scenario is when a left hand CP (LCP) or a right hand CP (RCP) signal arrived at this receiver. If the phase of the LO1 and LO2 are equal, the in-phase information I is seen at the first receiver branch, and the quadrature information Q is seen at the second receiver branch.

The receiver may also be driven with a dual circularly polarized antenna. A phase difference of 90° is then required for the extract of linearly cross-polarized waves. The reception modes of this receiver configuration also listed in Table I.

V. Reconfigurable Circuit Realization

The receiver circuitry may be divided into two portions: the broadband front-end down-convention circuitry and the narrowband phase distribution circuitry. Such group is created based on the feasibility of integration.

To demonstrate feasibility of this analog signal processing function a reconfigurable receiver circuit is developed using

TABLE I
OPERATION MODES OF THE RECONFIGURABLE RECEIVER

Wave Polarization	**Receiver with dual LP antenna**								**Receiver with dual CP antenna**							
	$\phi_2 = \phi_1$				$\phi_2 = \phi_1 + 90°$				$\phi_2 = \phi_1$				$\phi_2 = \phi_1 + 90°$			
	Va	Vb	Vc	Vd	Va	Vb	Vc	Vd	Va	Vb	Vc	Vd	Va	Vb	Vc	Vd
Vertical			X	O	-Q	I					X	O	-Q	I		
Horizontal			O	X	I	Q					O	X	I	Q		
+45° LP	O	X			O	X			Q	I					X	O
-45° LP	X	O			X	O			I	Q					O	X
LCP	I	Q					O	X	X	O			X	O		
RCP	Q	I					X	O	O	X			O	X		

Note: I and Q are in-phase and quadrature information of a modulated bandpass signal. O and X means the complete reception and rejection of a wave with regards to its cross-polarized counterpart.

RFIC based hardware reported earlier [19]. The phase shifters are replaced by a surface mount 90° hybrid circuits and a Wilkinson power divider. RCP and LCP signals from a dual polarized antenna are emulated by an FR4 realized branch-line coupler. The down-converted signal is combined at baseband with a 6dB resistive combiner. The sum of the two mixer output in this setup is RCP, while the difference of the mixer outputs is LCP. The vertically and horizontally polarized waves are also emulated in another setup by replacing the 90° hybrid with a 180 degree coupler, and the reception of these two waves is also measured.

The cross-polarization ratio is defined as the difference between the received signal sum and difference at the baseband. The measured result is shown in Fig. 3. Here the local oscillator (LO) signal is chosen at 2.45GHz. As we can see from the plot, a cross-polarization of 14dB is achieved for a bandwidth of over 500MHz. This level of cross polarization is achieved without optimization for gain and phase balance on two down-conversion branches. To achieve better cross-polarization, the gain and group delay of the down-conversion branch should be balanced. A practical application may employ a phase shifter that is controlled by a commercial high resolution DAC (though low speed) to improve the cross-polarization ratio for a broad operating frequency range. The bandwidth of tuning circuit only affects the settling time during the switching of operation modes.

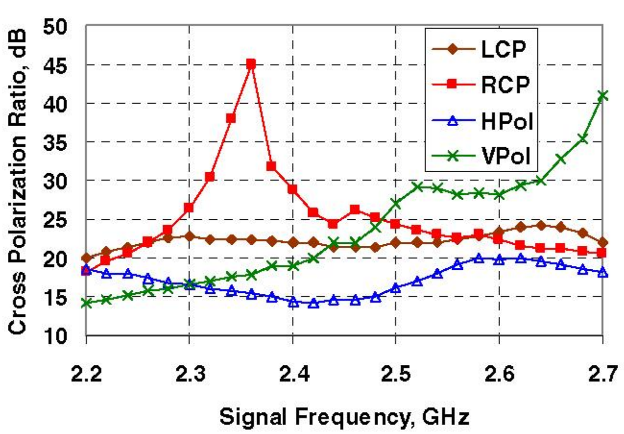

Fig. 3. Measured cross polarization ratio for the reception modes of RCP, LCP, vertical and horizontal polarizations.

VI. Conclusion

In this paper a reconfigurable receiver for any arbitrary antenna polarization is introduced, where by use of two tunable LO signals any polarized waves are properly received. A demonstrator circuit has shown an LCP, RCP, vertical and horizontal LP receiver where a 14dB cross-polarization gain is achieved. This analog signal processing function is advantageous for mobile communication applications with a limited digital signal processing resources.

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